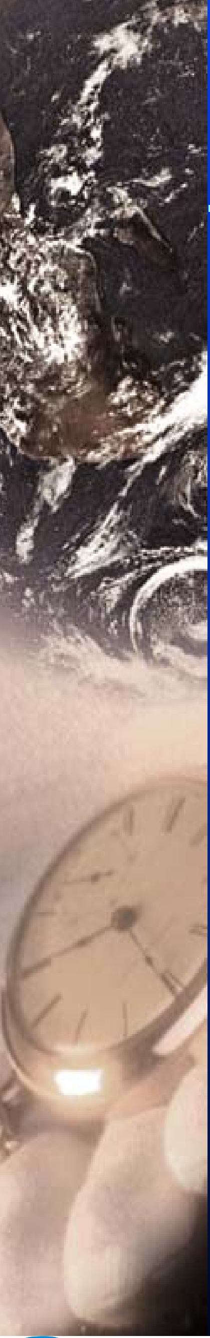

Predicting the Fuel Economy Impact of "Cold-Start" for Reformed Gasoline Fuel Cell Vehicles

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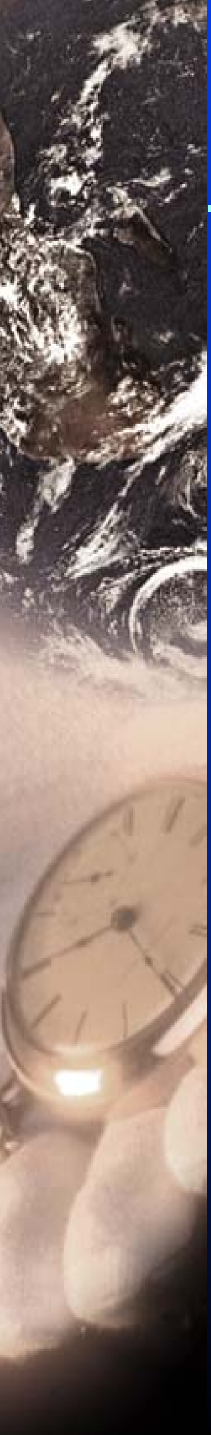
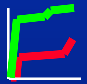
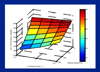
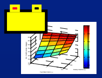
Outline

- Objective of Study
  - 5 questions to be answered
- Results
  - Answers to the 5 questions
- Conclusions



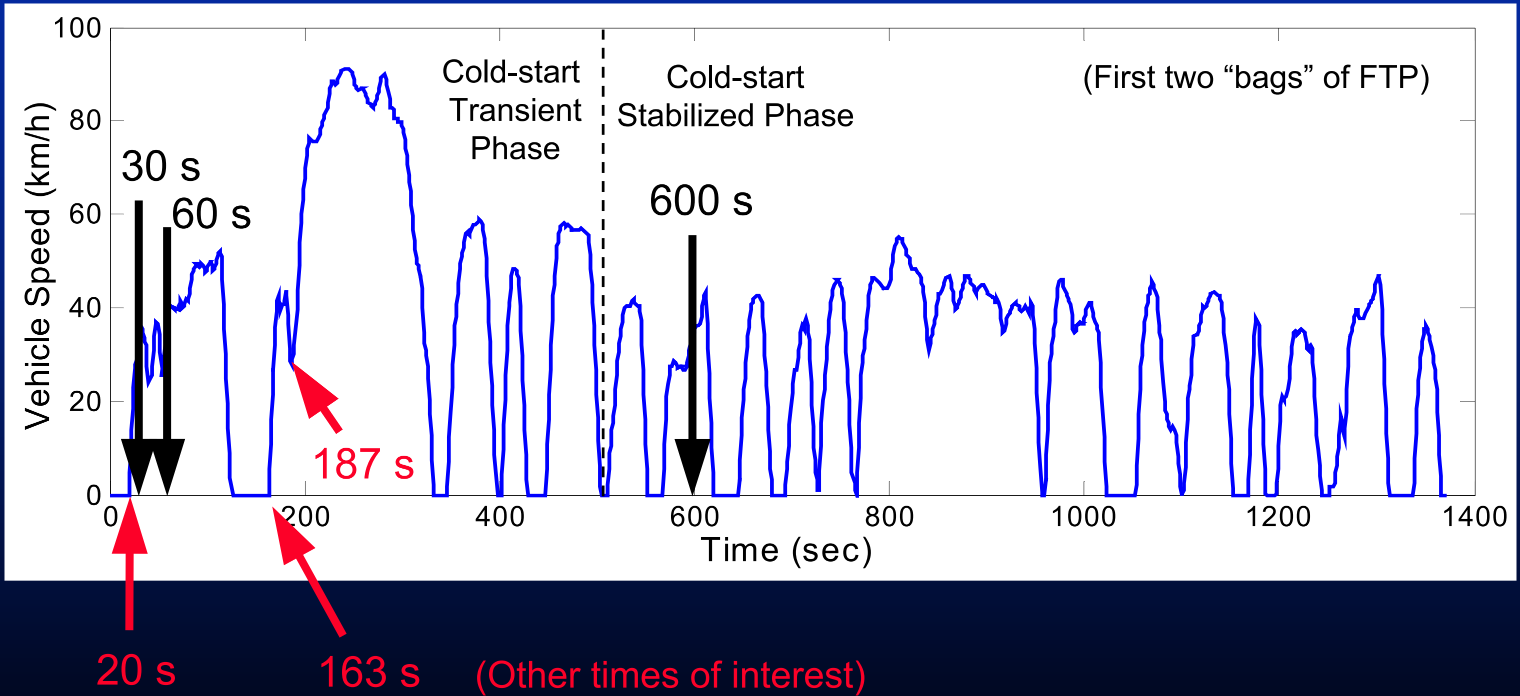
Objectives of Reformer Warm-up and Drive Cycle Interaction Analysis

- Objective: Articulate cold-start impact for a lightweight advanced FC vehicle system with on-board gasoline reforming
  
  - Minimum power and energy requirements for FTP drive cycle
  
  - Energy storage requirements if hybridization is required for startup
  
  - Determine off-cycle (non-FTP) requirements for reformer fuel cell systems
  
  - Fuel economy impacts of reformer warm-up on FTP
  
  - Examine combined reformer warmup and hybridization impacts

- Simulation results indicate …
  - Fuel economy penalty may be significant
  - Drive cycle demands could likely be met with relatively small battery…hybridization is beneficial
  - Off-cycle demands significantly greater than for FTP

Vehicle Level Impact of FTP with Overlays of DOE Reformer Fuel Cell Start-up Targets

- Fuel Processor to Generate H2-Containing Fuel Gas from RFG for 50 kWe Fuel Cell System:
  - 2001 status: <10 minutes (600 sec)
  - 2005 target: < 1 minute (60 sec)
  - 2010 target: < 0.5 minute (30 sec)



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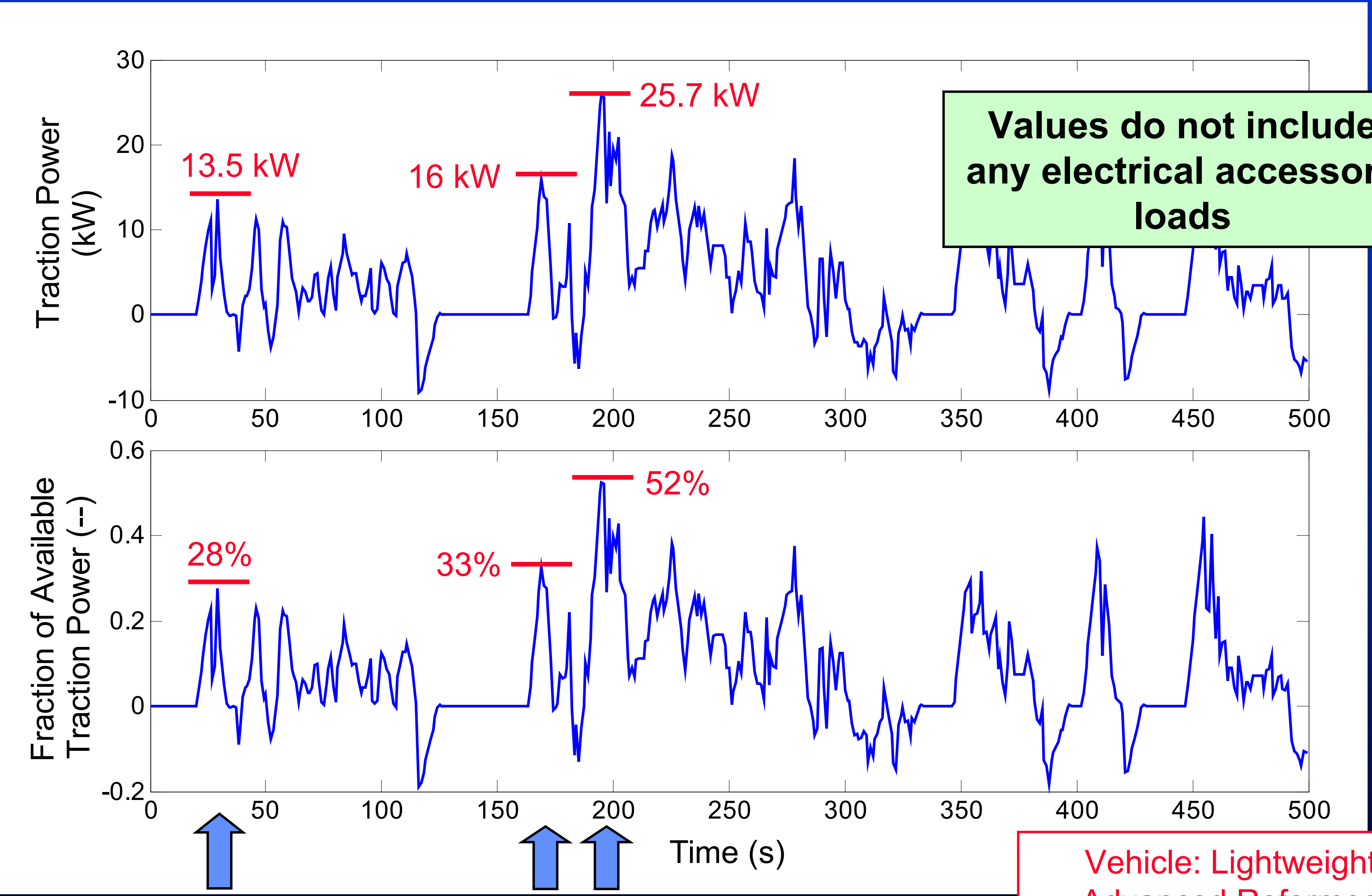
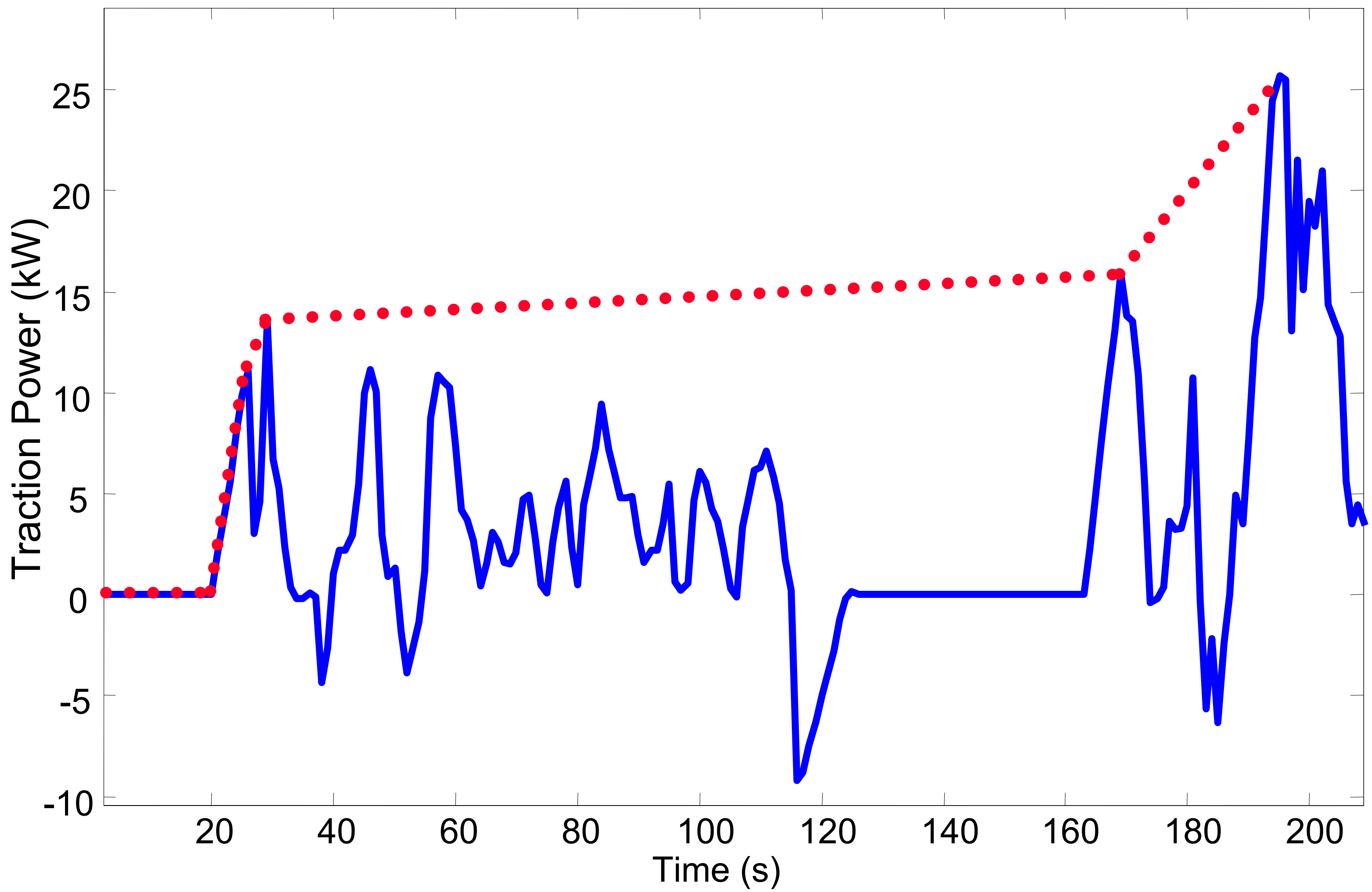
ADVISOR Simulations Calculated Power Requirements for First Part of FTP



Values do not include any electrical accessory loads

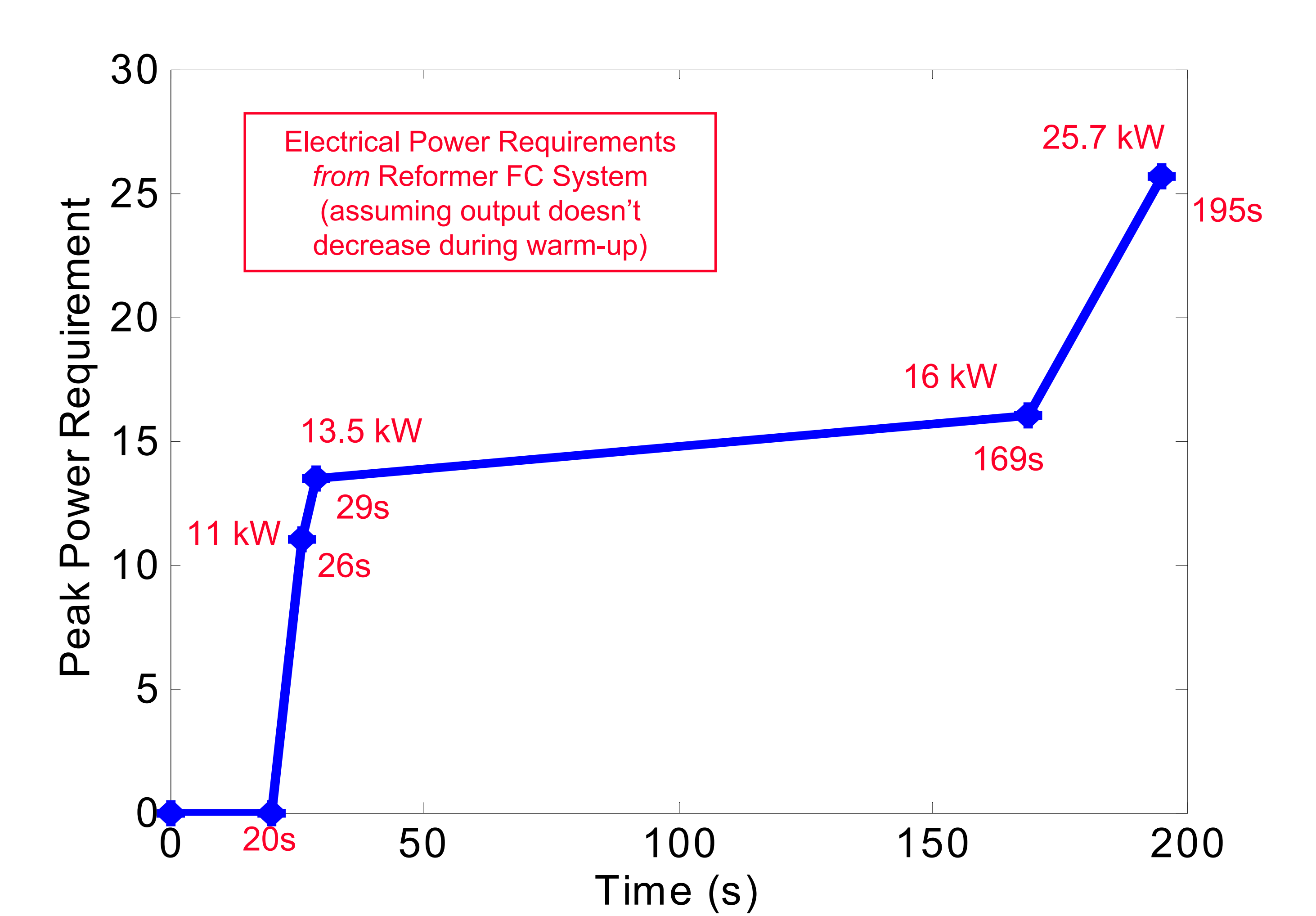
Vehicle: Lightweight Advanced Reformed Fuel Cell Vehicle (50 kWe)

Drawing Power Envelope for First 200 Seconds of FTP for this Vehicle



Vehicle: Lightweight Advanced Reformed Fuel Cell Vehicle (50 kWe)

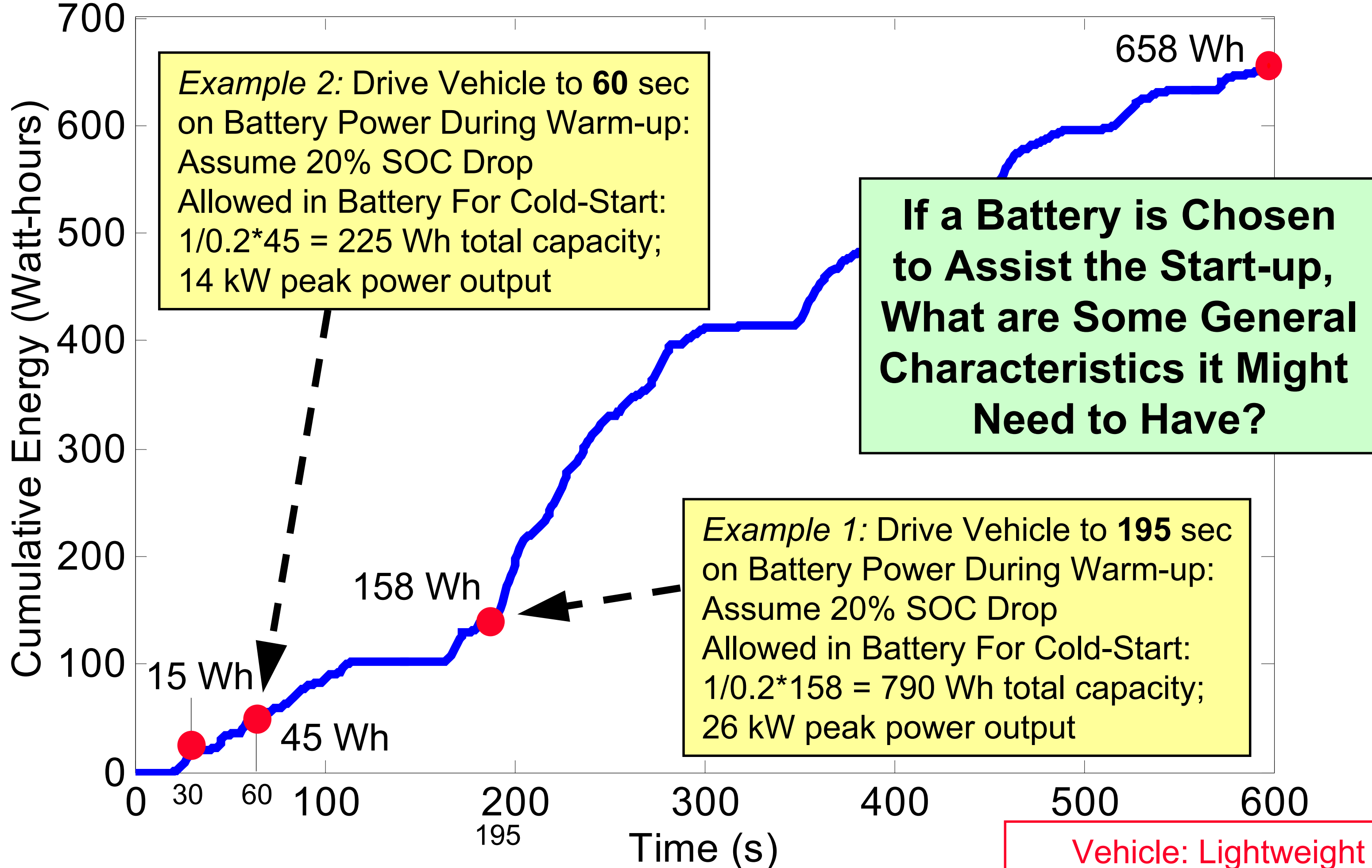
Resulting Minimum Power Requirements of FC System During First 200 seconds



* Does not include accessory loads

Vehicle: Lightweight
Advanced Reformed
Fuel Cell Vehicle (50 kWe)

Cumulative FTP Cycle Energy Required for Lightweight Advanced Vehicle (at motor terminals)



*** Does not include accessory loads or battery efficiency**

Vehicle: Lightweight Advanced Reformed Fuel Cell Vehicle (50 kWe)

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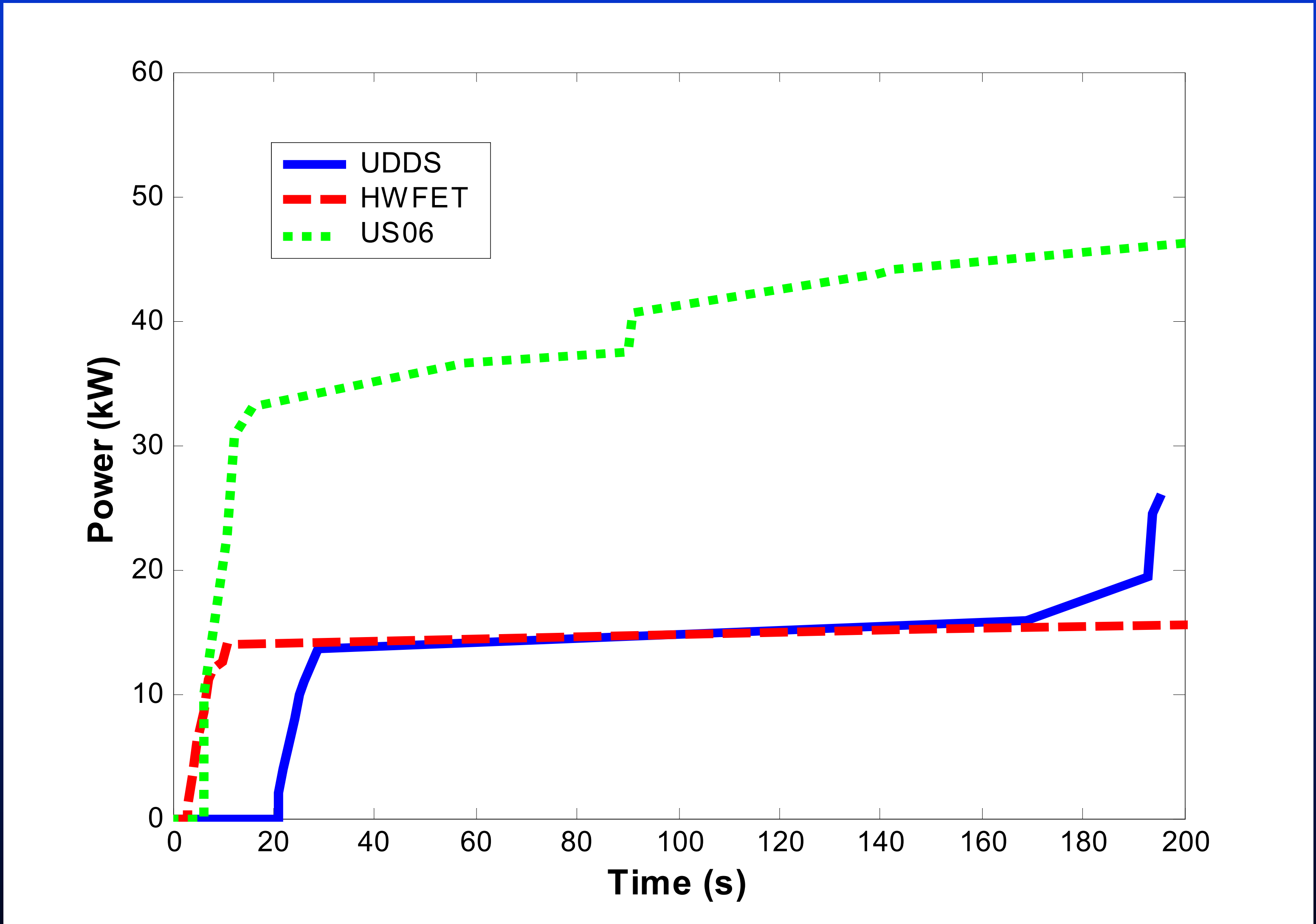
Comparison of FTP Battery Energy Requirements to Commercial HEVs

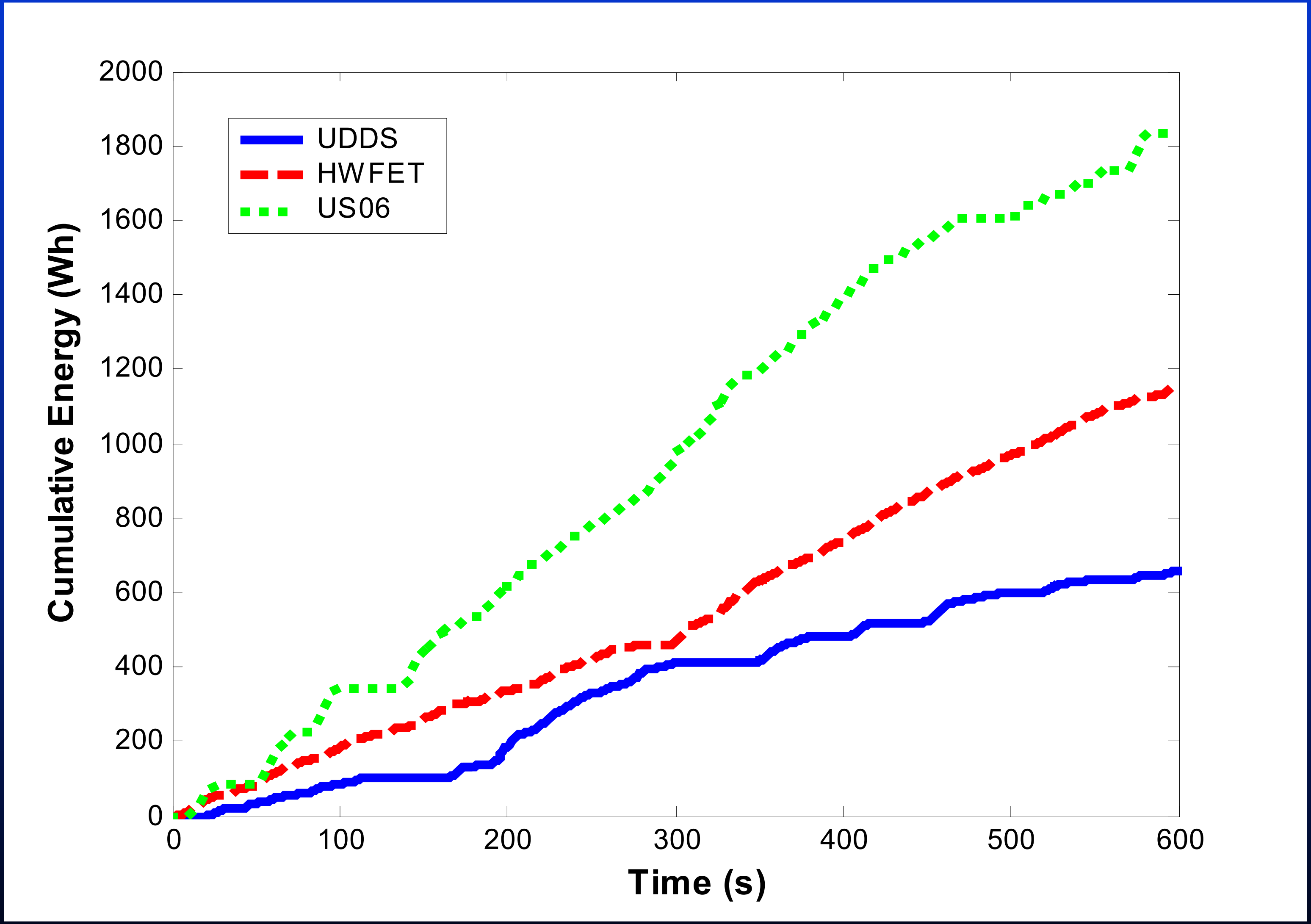
Reformer Warmup Time (s)	Power (kW)	Cum. Raw Energy [Usable] (Wh)	SOC Window (%)	Nom. Battery Pack Total Energy (Wh)
30 s	13.5	15	20	75
60 s	13.5	45	20	225
195 s	25.7	158	20	790
10 min	25.7	658	20	3290
Toyota Prius	25	--	~5	1781
Honda Insight	6	--	~10	936
Honda Civic	n/a	--	n/a	864

- **Drive cycle traction power and energy demands satisfied with relatively small battery**

Comparing Peak Power Requirements for UDDS with Highway and US06 Cycles



Comparing Energy Requirements for UDDS with Highway and US06 Cycles

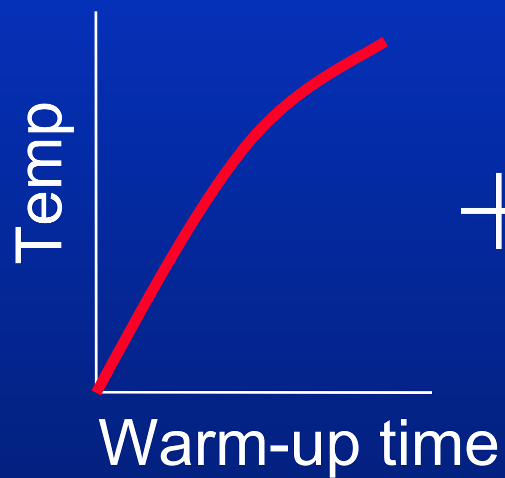


Tabulating Power and Energy Differences Between the 3 Cycles

Reformer Warmup Time	Drive Cycle	Power (kW)	Cumulative Raw Energy [Usable] (Wh)	Nominal Battery Pack Total Energy (Wh)
30 s	UDDS	13.5	15	75
	HWFET	14.0	59	295
	US06	34.2	82	410
60 s	UDDS	13.5	45	225
	HWFET	14.3	112	560
	US06	36.7	154	2800

Power Requirement of US06 is ~3X larger; Energy requirement is 5-10X larger

Methodology for Calculating Fuel Economy Impact of Reformer Startup



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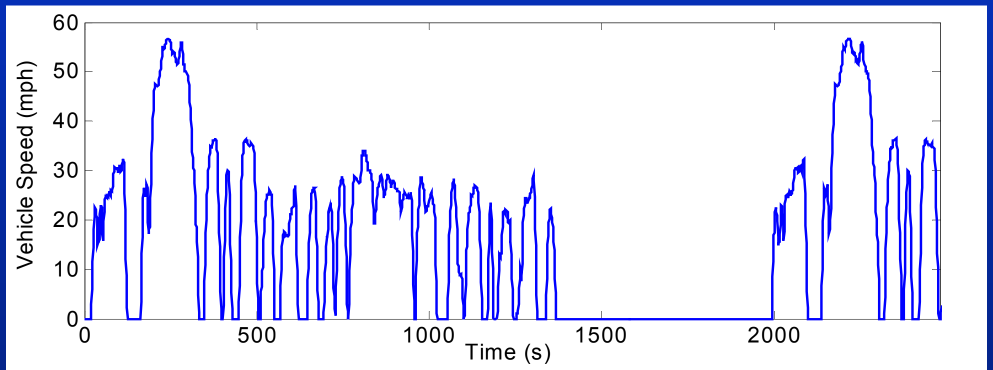
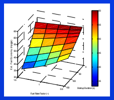
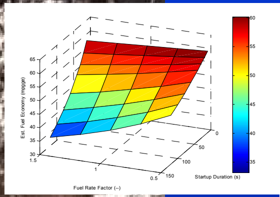


Emissions/fuel use sampled during whole period

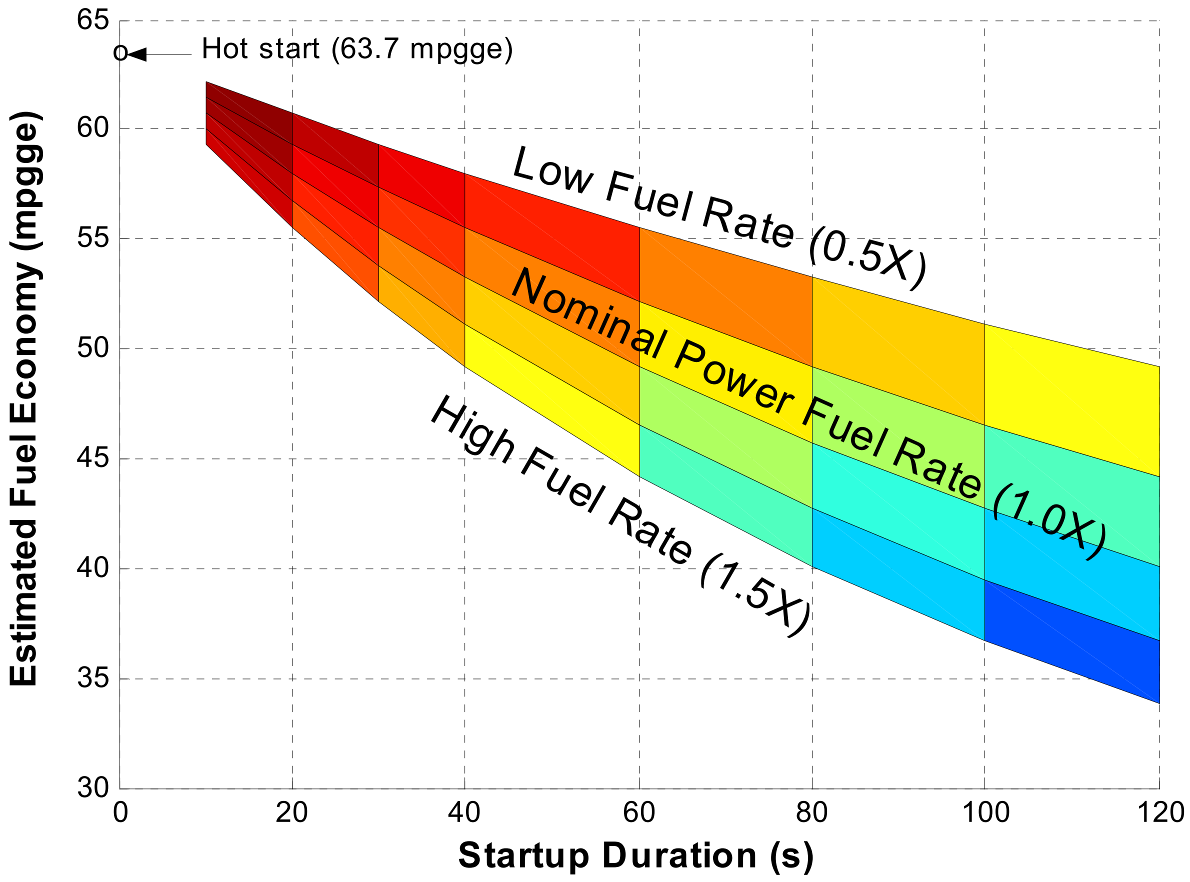
$$\text{Total Fuel Consumption} = \frac{\text{Fuel}_{\text{Reformer Warm-up}} + \text{Fuel}_{\text{Drive Cycle}}}{\text{Total Distance}}$$

Energy Cost (and Impact on FTP FE) of Having a Pre-Cycle Warm-Up (while stationary)





- **Fuel economy penalty significant if duration is long or fuel rate is high**



Fuel Rate Factor Is Multiplier of Fueling Rate at Peak Power

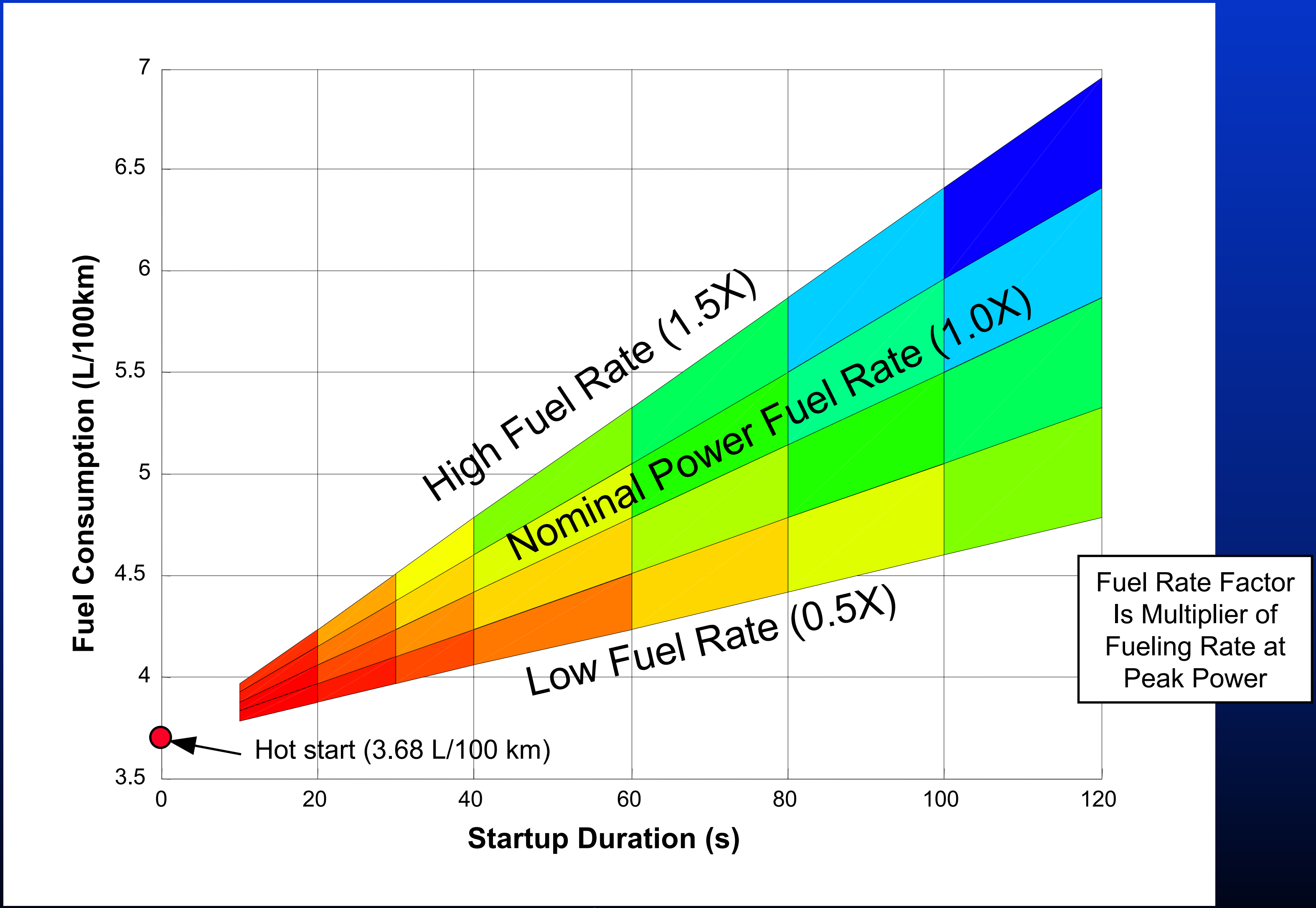
Note: baseline vehicle gets

61.7 (city)

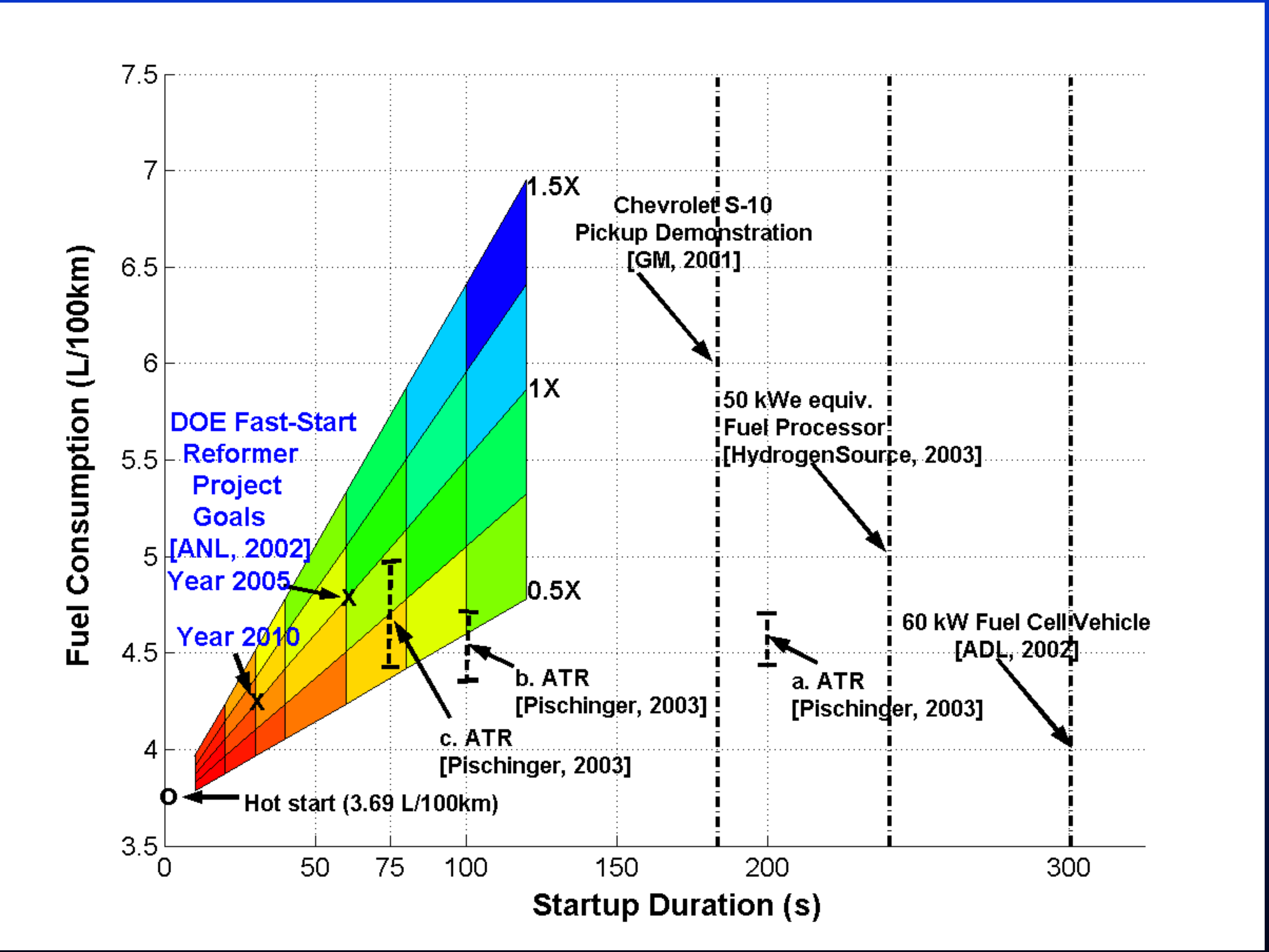
85.2 (highway)

70.5 (combined)

Looking at Results in L/100 km Makes Linear Relationship Clear

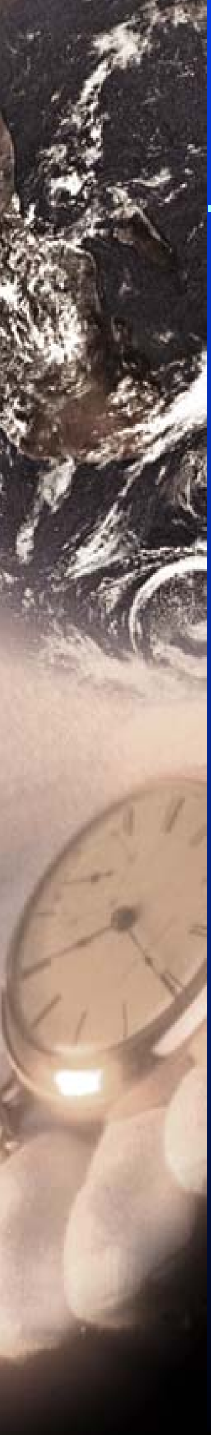


DOE Goals and Benchmark Studies/Hardware Indicate Appropriate Range of Interest Has Been Selected

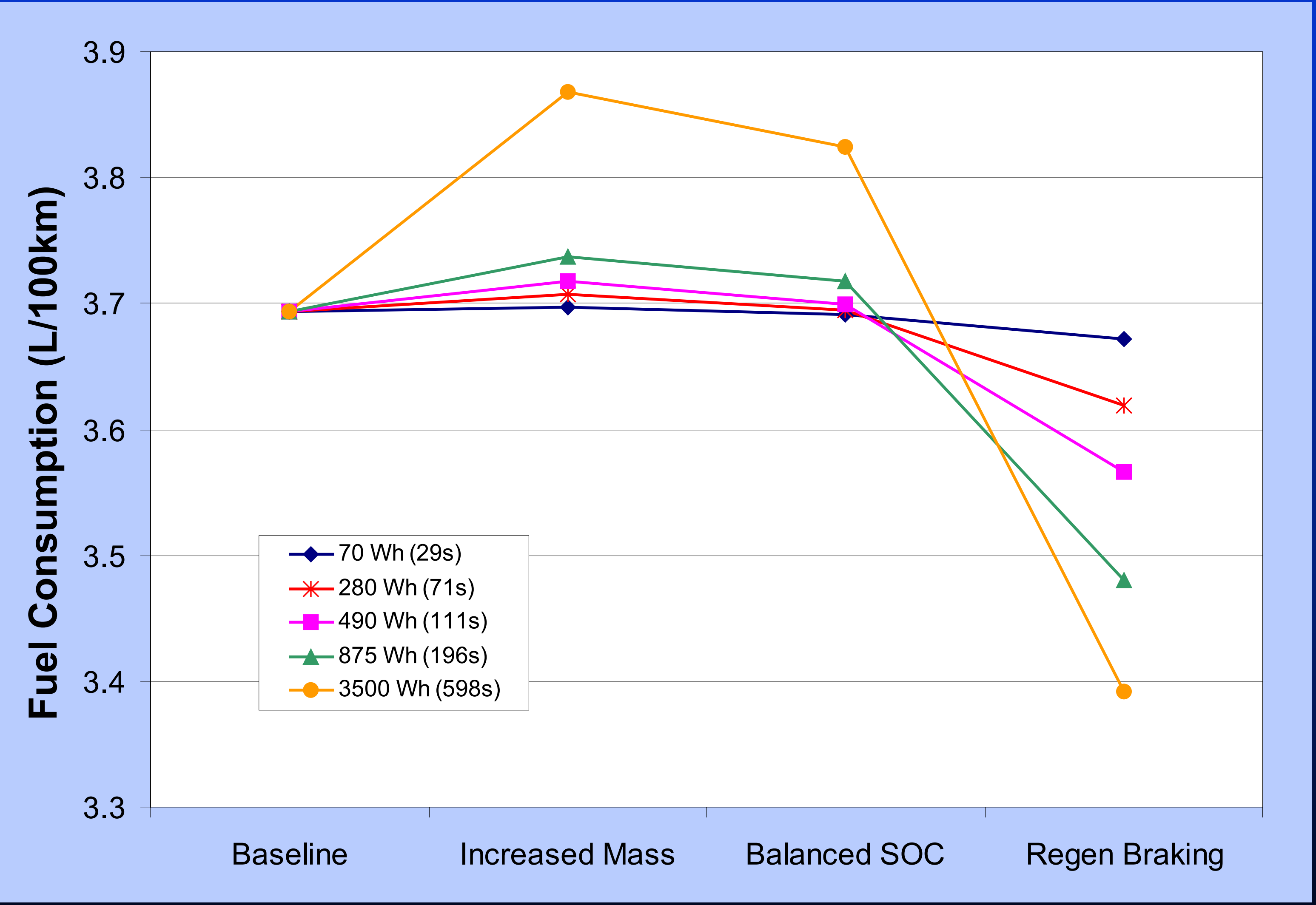


Examining Combined Impact of Hybridization and Cold-Start: Assumptions

Assumptions	Value	Units
Battery Energy Density	35	Wh/kg
Battery Charging Efficiency	0.85	--
Power Electronics Efficiency	0.95	--
Fuel Cell Reformer System Peak Efficiency	0.43	--
Battery Capacity Usable Window	20	%
Fuel Lower Heating Value	42600	J/g
Fuel Density	749	g/L
Fuel Cell Peak Power Fueling Rate	3.25	g/s
Reformer Fueling Rate Factor	1.0	--



Fuel Consumption Impacts of Stepwise Application of Hybridization



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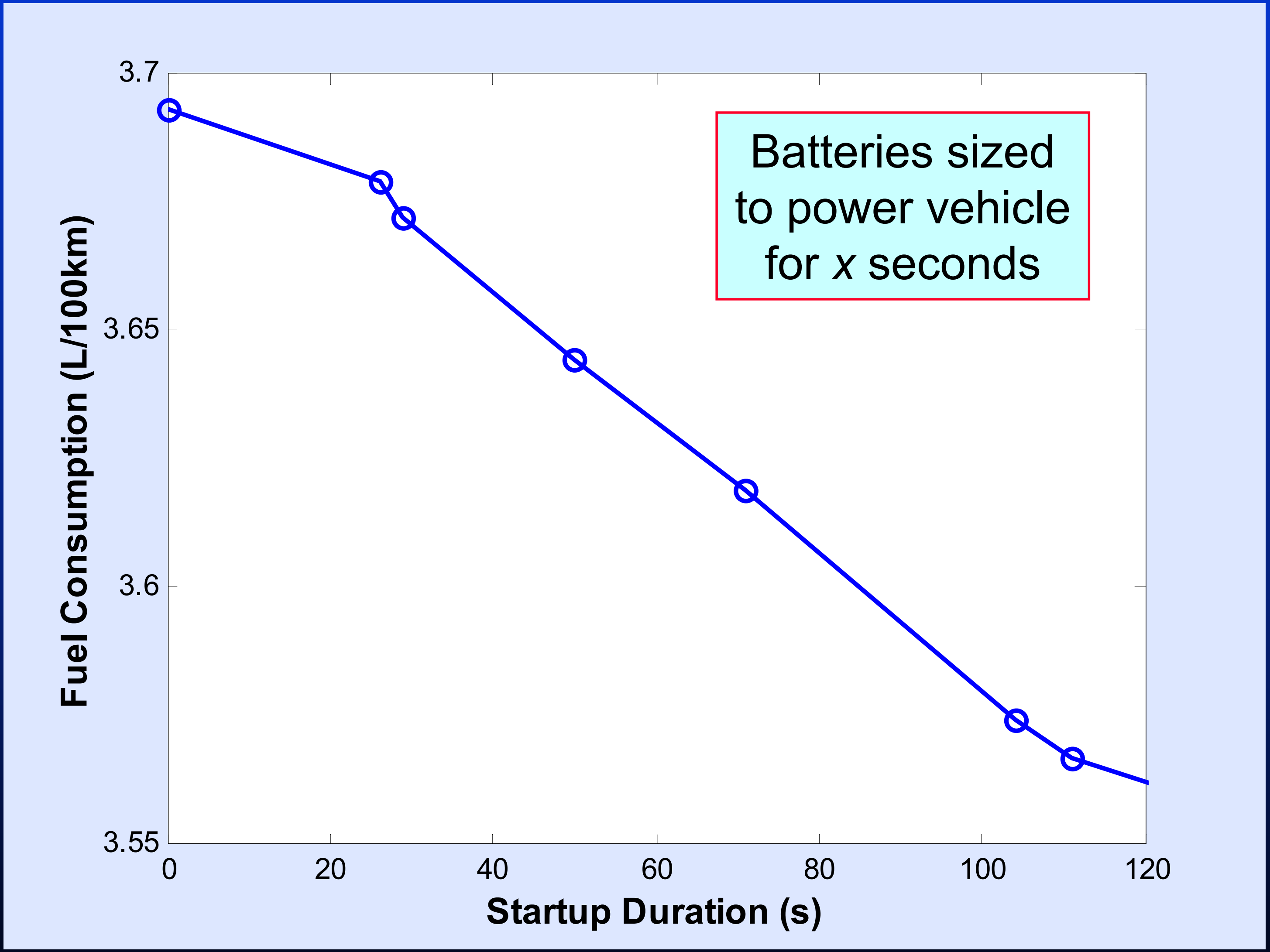
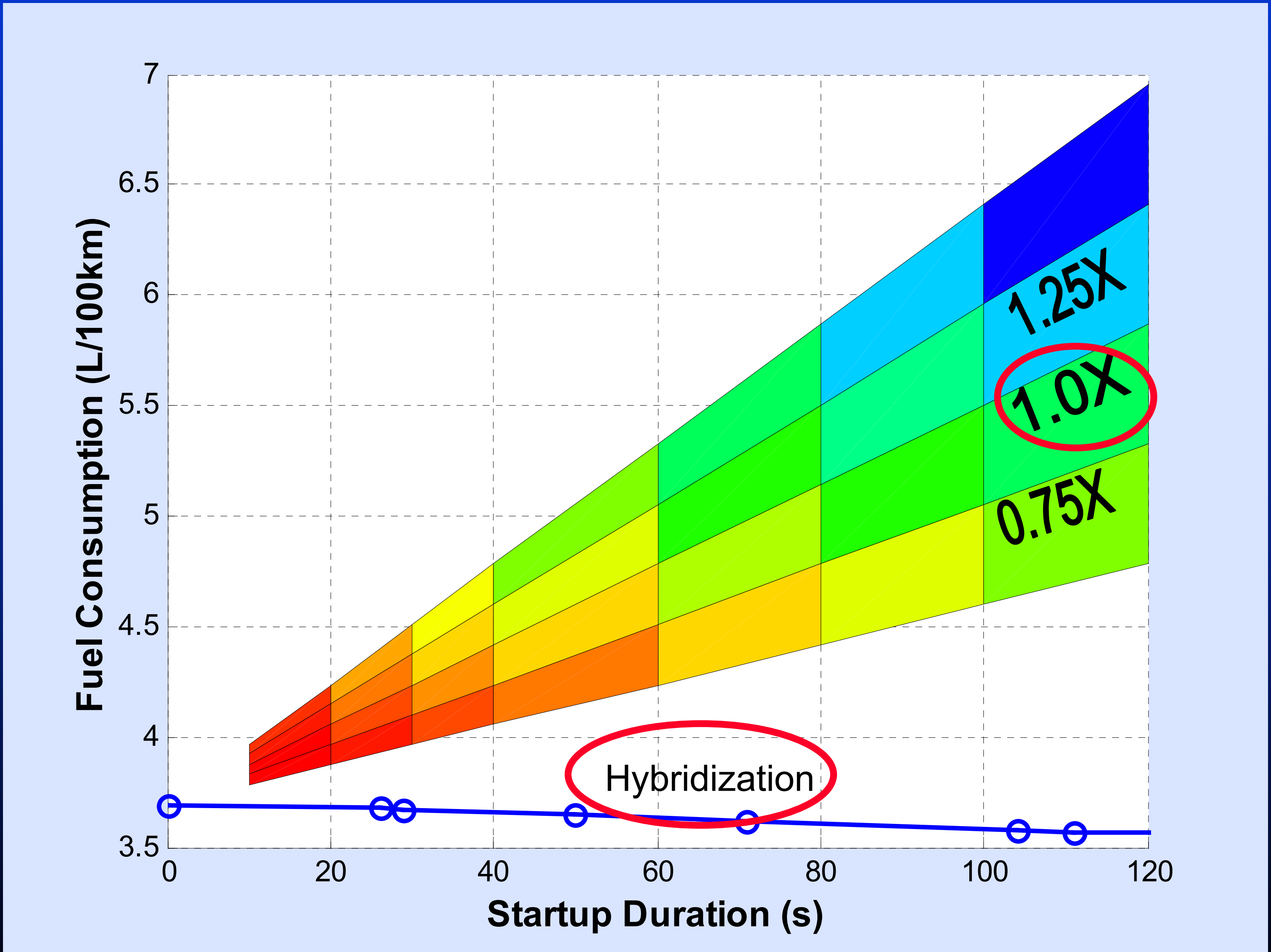
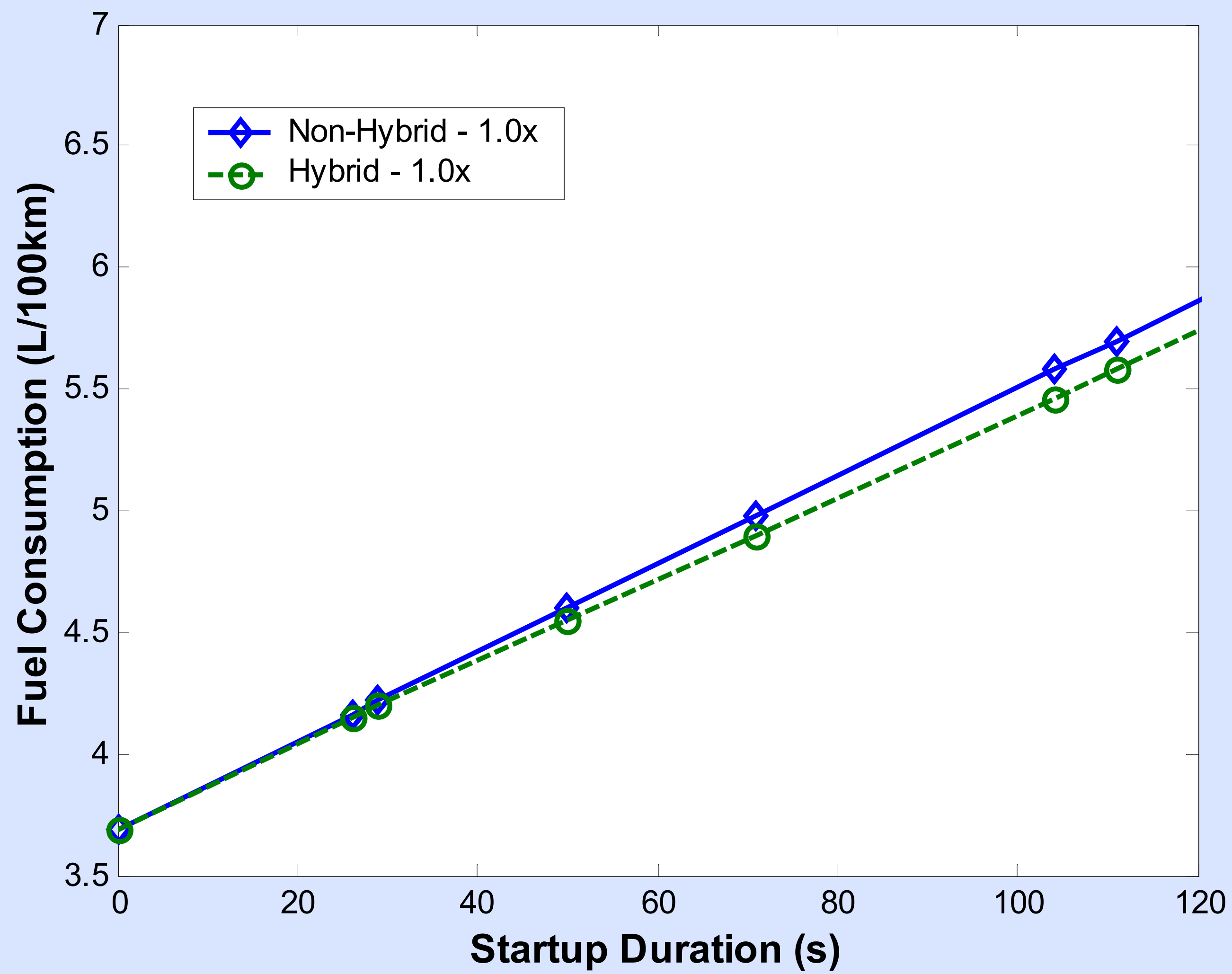
Cumulative Effects of Hybridization on Fuel Consumption Including Mass and Regen. Braking Impacts



Hybridization Impacts, Overlaid on Reformer Fuel Consumption Penalty



Fuel Consumption Improves Slightly with Hybridization for 1X Reformer Fueling Rate



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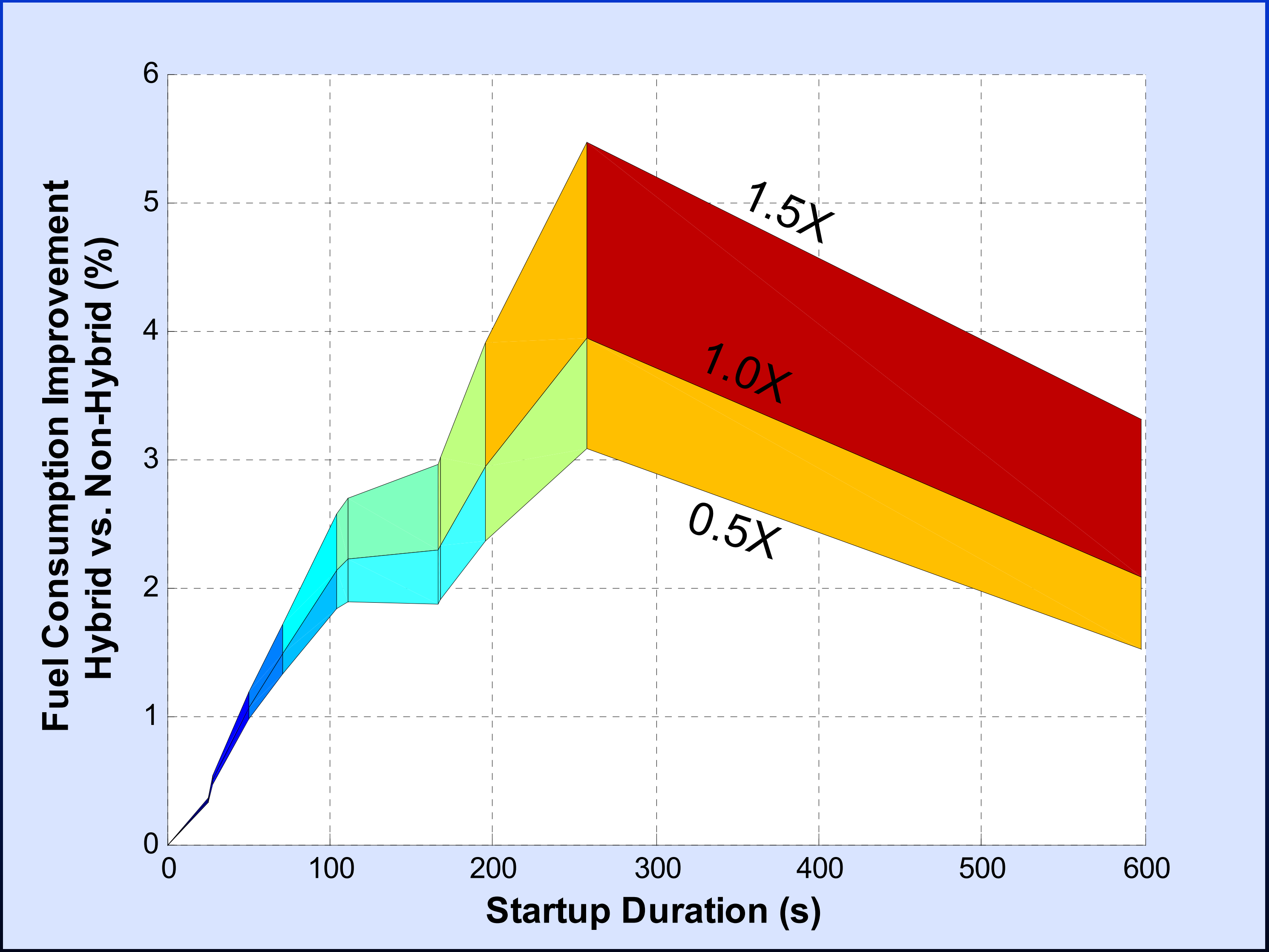
Fuel Consumption Improvement for Hybrid Features over Nonhybrid Scenario (%)



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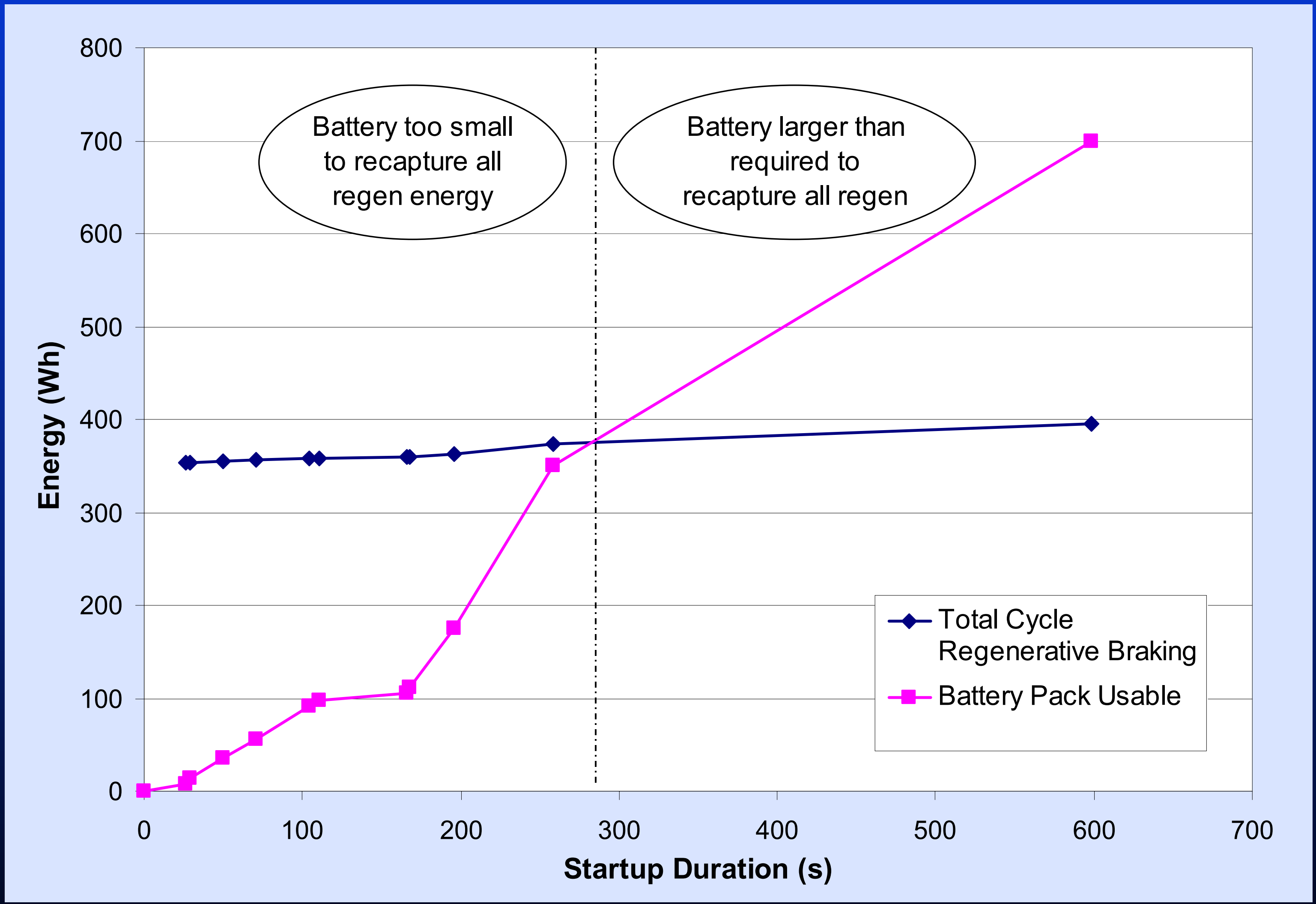
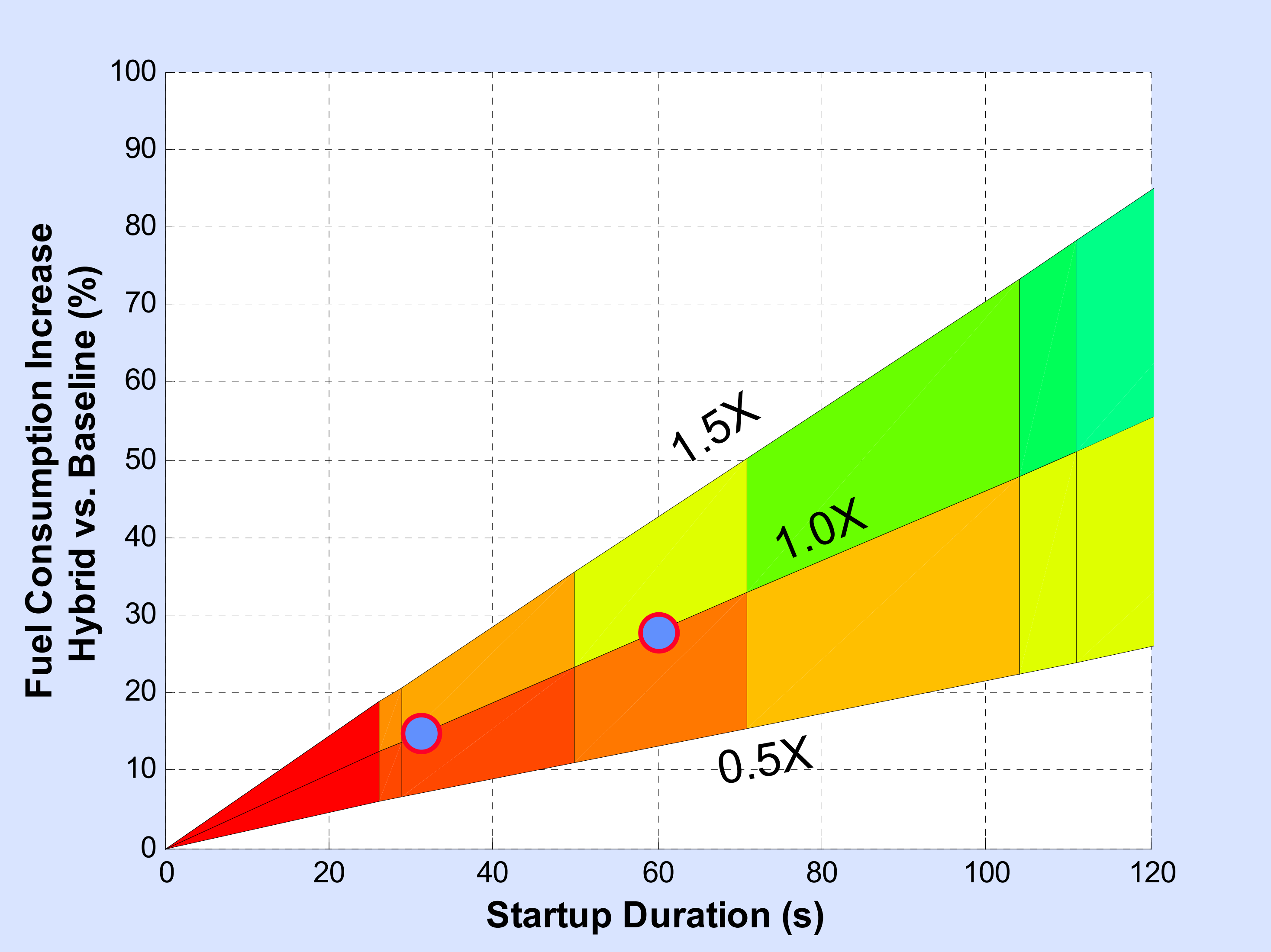
Optimal Battery Size Relative to Available Regenerative Braking Energy on FTP



Putting it all Together: Final Fuel Consumption Prediction Including Hybridization and Cold-Start (%)



Conclusions

- Minimum power and energy requirements for FTP drive cycle
  - ¼ power in 30 seconds, ½ power in ~3 minutes
  - Low energy requirements: small (225 Wh total cap) if full startup in 60 seconds, medium size (800 Wh total cap) if within 3 minutes
- Energy storage requirements if hybridization is required for startup
  - Requirements are in the range of current production HEVs
- Determine off-cycle (non-FTP) requirements for reformer fuel cell systems
  - Realistic drive-away requirements are significantly more challenging than FTP: 3X higher power and 5-10X higher energy on US06 vs. FTP
- Fuel consumption impacts of reformer warm-up on FTP
  - Impact expected to be 15-30% based on DOE fast-start targets
- Examine combined reformer warmup and hybridization impacts
  - Hybridization (sized only to overcome cold-start) improves fuel consumption by 3-6% and serves as an enabling technology for FCVs with reformers